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THE STRUCTURE AND SEDIMENTOLOGY OF RELICT TALUS, TROTTERNISH, NORTHERN SKYE, SCOTLAND

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ABSTRACT

Sections up to 3·5 m deep cut through the upper rectilinear segment of relict, vegetated talus slopes at the foot of the Trotternish escarpment reveal stacked debris-flow deposits intercalated with occasional slopewash horizons and buried organic soils. Radiocarbon dating of buried soil horizons indicates that reworking of sediment by debris flows predates 5·9–5·6 Cal ka BP, and has been intermittently active throughout the late Holocene. Particle size analyses of 18 bulk samples from these units indicates that *c*. 27–30 per cent of the talus deposit is composed of fine (<2 mm) sediment. Sedimentological comparison with tills excludes a glacigenic origin for the talus debris, and the angularity of constituent clasts suggests that *in situ* weathering has been insignificant in generating fine material. We conclude that the fine sediment within the talus is derived primarily by granular weathering of the rockwall, with syndepositional accumulation of both fine and coarse debris, implying that *c*. 27–30 per cent of rockwall retreat since deglaciation reflects granular weathering rather than rockfall. The abundance of fines within the talus deposits is inferred to have been of critical importance in facilitating build-up of porewater pressures during rainstorms, leading to episodic failure and flow of debris on the upper parts of the slope. A wider implication of these findings is that the mechanical properties of talus slopes cannot be regarded as those of free-draining accumulations of coarse clasts, and that models that treat talus slopes as such have limited value in explaining their form and evolution. Our findings lend support to models that envisage the upper straight slope on talus accumulations as the product of mass-transport as well as rockfall, and indicate that episodic debris flow has been the prrimary agent of mass-transport at this site. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: talus; debris flow; slopewash; rockwall retreat; granular weathering; Scotland

INTRODUCTION

Talus slopes are steep accumulations of rockfall-derived debris that have formed at the foot of cliffs. In Great Britain, most talus slopes are vegetated and essentially relict features, believed to have formed mainly under periglacial conditions during the Late Devensian Lateglacial, with only modest addition of rockfall debris under the milder conditions of the Holocene (Ballantyne and Eckford, 1984; Kotarba, 1984; Ballantyne and Kirkbride, 1987; Ballantyne and Harris, 1994). The talus accumulations of upland Britain comprise both talus cones and talus sheets. The former are widespread below rock gullies, but talus sheets reflecting more uniform delivery of rockfall debris are restricted to the lower parts of relatively ungullied cliffs.

In profile, rockfall-dominated talus slopes usually comprise two main units: a near-rectilinear upper slope resting at 33–40°, and a basal concavity (Howarth and Bones, 1972; Young, 1972; Chandler, 1973; Statham, 1973, 1976; Kotarba, 1976; Francou and Manté, 1990; Francou, 1991). Active examples generally support a complete cover of coarse debris that often displays a general downslope increase in the size of surficial clasts, termed fall-sorting. Most studies of talus accumulations have focused on two principal concerns: first, the nature of formative processes, and second, the relationship between such processes and slope form. Three broad models of talus accumulation have been proposed. Some researchers have explained talus morphology and fall-sorting in terms of the ‘angle of repose’ of debris redistributed by shallow debris slides or ‘dry avalanches’ (e.g. Rapp, 1960; Howarth and Bones, 1972; Carson, 1977; Whitehouse and McSaveney, 1983). Others have emphasized the impact energy of discrete rockfalls as the dominant control on form and sediment distribution

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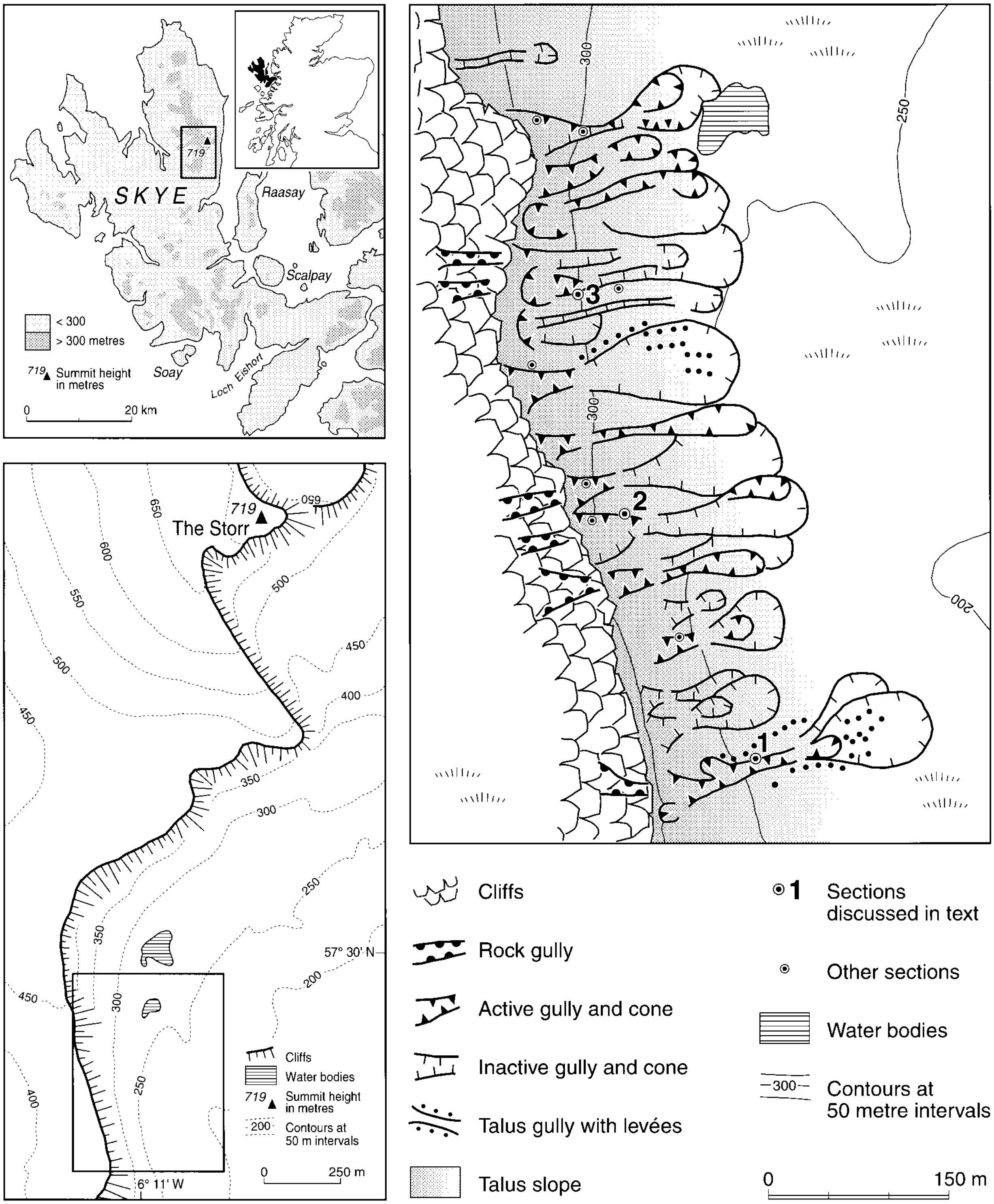

Figure 1. Geomorphology and location of the study site at the south end of the Trotternish escarpment, Isle of Skye, Scotland, showing the position of the sections discussed in the text and other excavated sections

Figure 2. Study site from the southeast. Deep gullies are incised into the otherwise vegetated slope, and provided access to the internal structure of the deposit

(e.g. Statham, 1973, 1976; Kirkby and Statham, 1975). More recently, some researchers have attempted to reconcile these views by explaining talus morphology and surface sedimentology in terms of a combination of rockfall deposition and subsequent transfer of debris down the upper straight slope by other processes (Statham and Francis, 1986; Francou and Manté, 1990; Francou, 1991).

Little research has been devoted to the internal architecture of talus slopes. Shallow exposures in talus accumulations suggest that the surface layer of coarse debris overlies a poorly sorted diamicton in which fine-grained sediments are abundant (Church *et al*., 1979; Åkerman, 1984; Selby, 1993), and a deeper exposure in a relict talus sheet in northwest Scotland has revealed that a predominantly clast-supported diamicton underlies a thin surface layer of openwork debris (Salt and Ballantyne, 1997). This paper reports the results of research on the internal structure and sedimentology of a relict talus slope on the Trotternish Peninsula, northern Skye, Scotland. Particular attention is devoted to: (1) describing and interpreting the internal structure of the talus; and (2) establishing the origin of the fine fraction within the talus debris. The implications of these findings for talus slope evolution are then considered.

THE TROTTERNISH TALUS SLOPES

The Trotternish escarpment in northern Skye extends north–south for 24 km along the length of the Trotternish Peninsula (Figure 1), and is fringed along most of its length by vegetated relict talus slopes. Numerous deep gullies are incised through the talus sheets, enabling close examination of their structure and composition. Detailed investigations of the internal characteristics of these slopes were concentrated along a 750 m long stretch of talus at the southern end of the escarpment (57°29′N 6°10′W; Figures 1 and 2). The foot of the talus lies at an altitude of 240–250 m, its crest at 310–340 m and the top of the headwall exceeds 400 m. The headwall is composed of westward-dipping Palaeogene basalts and tuffs, into which numerous olivine–dolerite sills and dykes are intruded (Anderson and Dunham, 1966; Bell and Harris, 1986). With the exception of the highest summits, the area was over-ridden by the Late Devensian ice sheet (Ballantyne, 1990, 1994). Cosmogenic ^{36}Cl ages obtained from glacially abraded rock outcrops on the col south of The Storr (Stone *et al*., 1998; Figure 1) indicate deglaciation of the study site soon after *c*. 17·6 Cal ka BP (*c*. 14·8 ka BP). Though two small glaciers subsequently developed northeast and north of The Storr during the Loch Lomond Stade of *c*. 12·9–11·5 Cal ka BP, the study site was not reoccupied by glacier ice at this time (Ballantyne, 1990). Large-scale postglacial

landslips have affected several parts of the escarpment, but the landslip deposits downslope from the study site are ice-moulded features that predate the passage of the last ice sheet (Anderson and Dunham, 1966; Ballantyne, 1991a,b). The talus slopes investigated thus appear to have developed over a timescale of perhaps 17 ka, under both periglacial and temperate maritime conditions, and have not been affected by large-scale postglacial landsliding.

In profile, the talus accumulations of Trotternish comprise both the upper rectilinear slope and basal concavity characteristic of mature rockfall accumulations. The mean gradients of transects surveyed up the upper rectilinear slopes range from 36° to 42° and are thus similar to (but slightly steeper than) upper slope gradients for talus slopes elsewhere in upland Britain, for example 32–40° in Wales (Tinkler, 1966; Statham, 1973), 33–38° in the Cuillin Hills of Skye (Statham, 1976) and 32–39° for sites elsewhere in Scotland (Ballantyne and Eckford, 1984; Ward, 1985). Talus maturity is indicated by the H_o/H_i ratio, where H_o is the vertical height of the talus and H_i is the height of the entire slope (talus plus rockwall). The mean H_o/H_i ratio for the talus slopes investigated on Trotternish is 0·57, slightly lower than values reported for relict Lateglacial taluses elsewhere in Scotland, but much higher than those reported for talus cones that formed during the Holocene in sites that were reoccupied by glacier ice during the Loch Lomond Stade (Statham, 1976; Ballantyne and Eckford, 1984; Ballantyne and Harris, 1994, p. 224). Ungullied sections of the talus sheet support a complete vegetation cover of grasses, sedges and woody shrubs (especially *Calluna vulgaris* and Ericaceae), but many gullies are fresh and unvegetated. Numerous boulders protrude above the vegetation mat on lower slopes, especially where the levées of debris flows extend downslope from active gullies.

INTERNAL STRUCTURE

Ten vertical section up to 3·5 m deep were excavated in the walls of gullies cut in talus at the study site. As all sections revealed broadly similar structural and sedimentological characteristics, three representative examples (1–3 in Figure 1) are considered in detail here. All sections were excavated in the mid-slope zone of the upper rectilinear slope, where bedrock exposures in gully floors indicate a minimum talus thickness of 2·0–5·0 m, though the deposit apparently thickens downslope from the top of the basal concavity. The sections were photographed and logged, and bulk samples were withdrawn from certain minerogenic horizons for sedimentological analyses. In addition, samples from the top 5 mm of the lowermost buried organic soil horizon at sites 1–3 were collected for radiocarbon analyses, to allow the period over which the overlying sediments had accumulated to be determined.

All excavated sections reveal that the uppermost 1·5–3·0 m of the deposit, rather than comprising the framework of openwork clasts characteristic of the surface of active taluses, are composed of stacked sediment units of variable composition, in some cases separated by thin peaty organic soils of varying maturity that represent the former ground surface (Figures 3 and 4). The depositional units are aligned approximately parallel with the ground surface, a feature previously observed in relict taluses elsewhere in Scotland (Kotarba, 1984; Salt and Ballantyne, 1997). Contacts are usually conformable over short distances, but some layers exhibit truncation and examples of horizons pinching out both upslope and downslope were observed. At the base of some sections (e.g. 1 and 2 in Figure 3) are massive clast-supported diamictons that may represent *in situ* rockfall debris, but the overlying sediments in all excavated sections are dominated by stacked matrix-supported diamictons, some of which contain distinct miniature shear structures subparallel to the surface (e.g. units 1·7, 2·2 and 3·4 in Figure 3) or lenses of fine gravel aligned downslope (e.g. units 1·7 and 3·11). Both structures are indicative of debris flow (sediment-gravity flow) deposits, emplaced during reworking of earlier sediments from upslope. In common with debris-flow deposits in other environments (e.g. Suwa and Okuda, 1980; Rapp and Nyberg, 1981; Wells and Harvey, 1987; Eyles *et al.*, 1988; Eyles and Kocsis, 1988; Nieuwenhuijzen and van Steijn, 1990; Derbyshire and Owen, 1990; Owen, 1991), the depositional facies in these units exhibit considerable variability. Clast size and the ratio of coarse to fine-grained (<2 mm) sediment vary between beds. Differences in matrix and packing characteristics are also visually evident. Some beds (e.g. unit 1·7) exhibit inverse grading, a characteristic attributed to dispersive forces within mobile debris flows, in which larger particles become relatively buoyant and move to the surface and margins of the flowing mass (Pierson, 1980; Takahashi, 1981; Nieuwenhuijzen and van Steijn, 1990; Bertran and Texier, 1994). In addition to

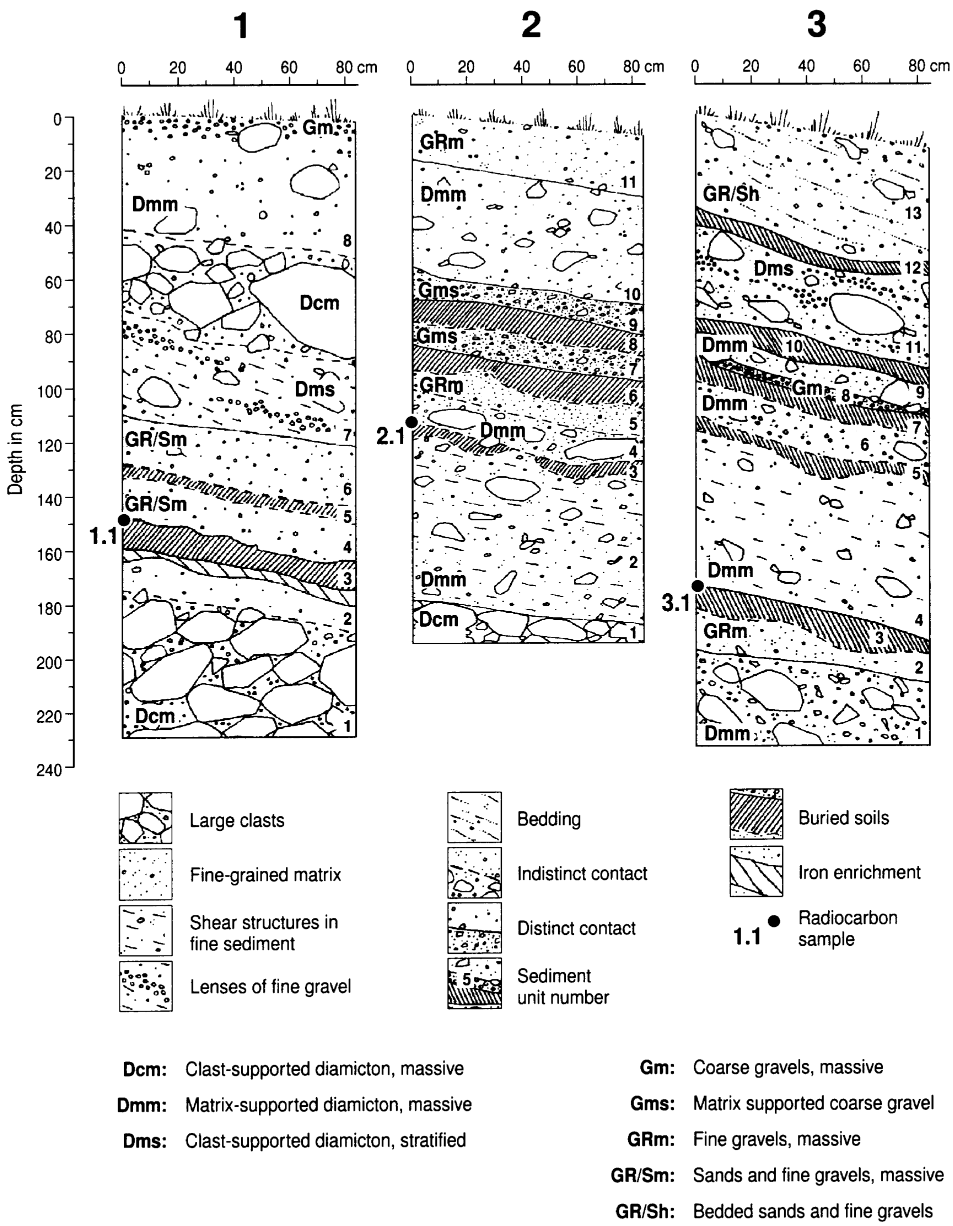

Figure 3. Logs of three representative sections cut through the upper straight slope of the talus at gully-side sites. Locations are shown in Figure 1. Sediment units are numbered along the right-hand side of each section

the diamicton units, most sections also revealed thinner beds of sand and fine gravel from which large clasts are absent. Some of these exhibit crude stratification (e.g. units 1·4, 1·6 and 3·13 in Figure 3) whilst others are massive and coarse-grained (e.g. units 2·5, 2·7, 2·9 and 3·8). These are interpreted as slopewash deposits, possibly reflecting the eluviation of fines from recently immobilized debris flows (Takahashi, 1991) or reworking of unvegetated debris-flow deposits during rainstorms.

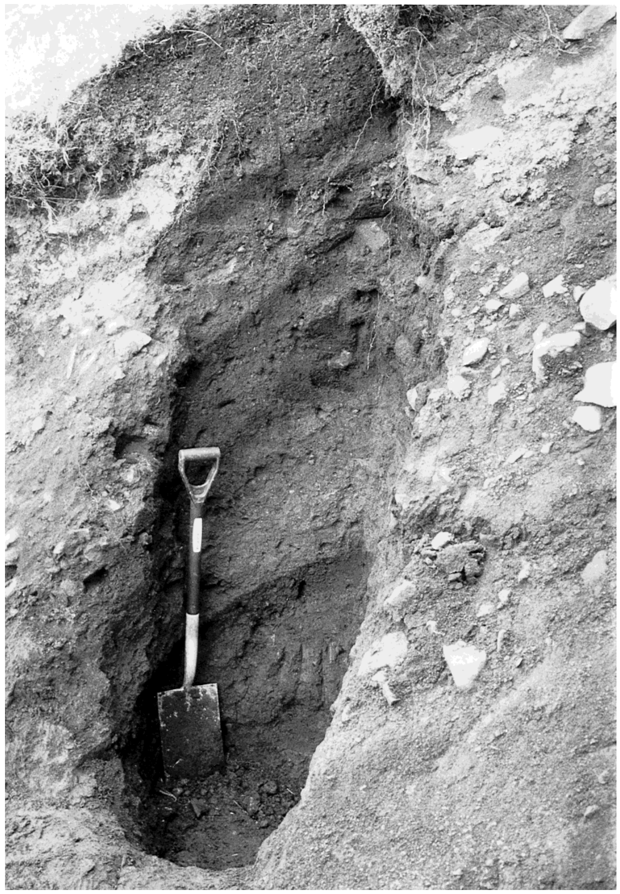

Figure 4. Section excavated to a depth of 2·3 m at site 3. Spade is approximately 1 m long. Note the multiple buried soil horizons (dark layers), with intervening matrix-supported diamictons (debris-flow deposits) and the slopewash deposit of sand and fine gravel at the top of the section

To test the hypothesis that the stacked diamictons represent reworking of talus sediments by debris flow, the orientation and dip of samples of 50 clasts with elongation (long axis:intermediate axis) ratios ≥1·5 were measured for six representative units. The results (Figure 5) were subjected to eigenvector analysis (Mark, 1973), which demonstrated that in five out of the six cases the orientation of principal eigenvector (V_1) lay within ±17° of slope aspect, confirming that the preferred orientation of clasts lies broadly in a downslope direction (Table I). The V_1 dip values fell within the range 19–31°, in all cases less than the local gradient, indicating a tendency for clasts to be imbricate upslope. Both features are characteristic of debris-flow deposits (Lindsay, 1968; Eyles and Kocsis, 1988; Ballantyne and Benn, 1994). Following the method proposed by Benn (1994), an isotropy index ($I=S_3/S_1$) and an elongation index ($E=1-S_2/S_3$) were calculated from the eigenvector data and plotted on a fabric shape triangle (Figure 6). The fabric shapes for all six samples fall within the field identified by Benn (1994) as representative for debris flows, and, with one exception, outside the field characteristic of *in situ* rockfall talus, thus supporting the initial interpretation of the stacked diamictons as debris-flow deposits.

The dominance in all 10 excavated sections of debris flow and wash deposits within the upper few metres of the talus accumulations implies that the form of the upper rectilinear slope reflects extensive episodic reworking of debris by debris flow and surface wash. The presence of buried soils of varying maturity between these minerogenic layers implies that episodes of sediment reworking were separated by prolonged periods of slope stability during which such soils developed. Minimum ages for the onset of reworking of sediments at sections 1–3 are given by radiocarbon dates obtained for the top 5 mm of the lowest organic soil exposed at each site (Figure 3 and Table II). Samples 2·1 and 3·1 yielded statistically indistinguishable ages (5005±50 a BP and 5050±50 a BP) that convert to a probable range of 5·9–5·6 Cal ka BP. As the soils from which these dates were

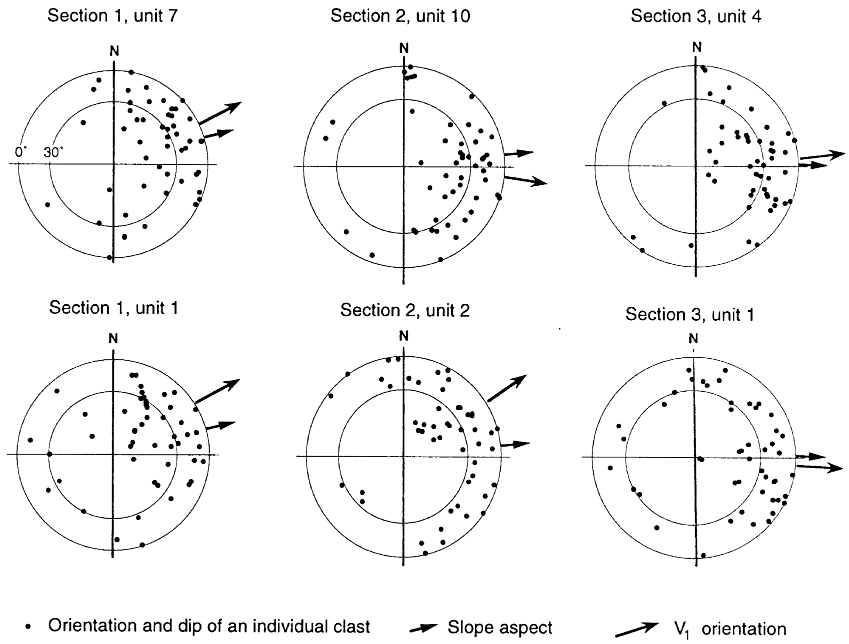

Figure 5. Orientation and dip of 50 clasts in six diamicton units from sections 1–3

Table I. Eigenvector V_1 and S_1 values for diamicton units in sections 1–3

Section	Depth (cm)	Unit	Slope aspect (degree)	V_1 orientation (degree)	V_1 dip (degree)	S_1
1	90	7	74	64	28	0·534
1	200	1	74	57	24	0·591
2	30	10	83	97	28	0·588
2	140	2	83	57	26	0·528
3	150	4	88	84	31	0·635
3	210	1	88	94	19	0·534

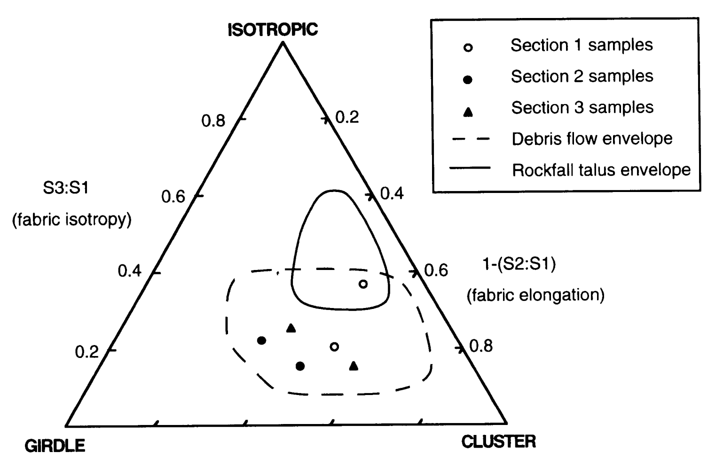

Figure 6. Eigenvector data depicted on a fabric shape triangle. The fabrics measured in the diamicton units all fall within the field identified by Benn (1994) as representative of debris-flow deposits, but only one sample also falls within the field for rockfall talus

Table II. Radiocarbon ages for the top 5 mm of the lowest organic soil at sections 1–3

Sample no.	Pit depth (cm)	Sample depth (cm)	Laboratory code	Radiocarbon age (^{14}C years BP)	$\delta^{13}C$ (‰)	Calibrated age range* (calendar years BP) 95% confidence (±2σ)
TR 1.1	229	149	SRR-5652	2225±40	–29·2	2338–2117
TR 2.1	194	112	SRR-5654	5005±50	–28·8	5906–5617
TR 3.1	235	178	SRR-5655	5055±50	–24·9	5913–5659

* Calibrated calendar ages were calculated using the CALIB rev 3.0 programme of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993).

obtained overlie earlier debris-flow deposits, these dates confirm that sediment reworking by debris flow was active prior to 5·9–5·6 Cal kaBP. The overlying stacked debris flow, wash and buried soil horizons indicate that episodic reworking of sediments continued throughout the Late Holocene. A calibrated age of *c*. 2·3–2·1 Cal ka BP was obtained for sample 1·1, obtained from a soil developed on a single thin debris-flow unit that overlies possible *in situ* rockfall deposits. This suggests that the onset of reworking was later on this section of the slope, although it is possible that earlier debris-flow units and/or buried soils at this exposure were removed by erosion prior to emplacement of the basal debris-flow unit.

The above findings demonstrate that rockfall accumulation has not been the sole agent of talus evolution on Trotternish, and that reworking processes (particularly debris flow) have played an important role in determining present slope form and structure. The radiocarbon age determinations imply that such processes have been intermittently operative from at least mid-Holocene times onwards, and possibly much earlier. These findings lend support to those models that envisage mass-transport as well as rockfall deposition on the upper rectilinear slope (Statham and Francis, 1986; Francou and Manté, 1990; Francou, 1991). It is also clear from the above findings that fine sediment is abundant within the talus, and has probably played a critical role in facilitating slope reworking. Debris flows on steep hillslopes generally occur when a build-up of porewater pressures within unconsolidated sediments causes a reduction in shearing resistance, leading to failure and flow. In fine sediments where drainage through internal voids is impeded, shallow failure and flow of debris is common on steep slopes during intense rainstorms (Rapp and Nyberg, 1981; Innes, 1983; Zimmermann and Haeberli, 1992). It is thus likely that the abundance of fines within the Trotternish talus accumulations has influenced slope evolution by facilitating downslope mass-transfer of debris by debris flow. The characteristics and origins of the fine fraction within these slopes are considered below.

SEDIMENTOLOGICAL CHARACTERISTICS

Particle-size analyses were carried out on 12 bulk samples from debris flow units and six samples from slopewash units. Laboratory analyses were confined to particles finer than 64 mm (–6ϕ). As the debris-flow deposits also contain clasts ≥64 mm in width, measurements were made in the field of the proportion of overall sample weight represented by clasts with intermediate axes exceeding 64 mm. This was achieved by excavating five large bulk samples (each >250 kg) from individual debris-flow units, separating out all clasts ≥64 mm in width, and weighing both the coarse clasts and residue using a spring balance. The results yielded an overall mean value of 55·0 per cent by weight coarser than 64 mm with a standard error of 5·2 per cent. Particles finer than 64 mm were wet-sieved at 1ϕf intervals down to 500 μm, and the granulometry of sediment finer than 500 μm was analysed using a Coulter Counter LS100.

The results (Figure 7) show marked contrasts in the particle-size distributions for wash deposits and debris-flow units. The wash layers are dominated by sand, with minor components of silt and fine gravel (both <20 per cent) a negligible (<1 per cent) clay content and no particles coarser than 8 mm, indicating deposition by surface flow of low competence. The debris flow samples contain <1 per cent clay and <10 per cent silt, but, in contrast to the wash samples, the sand fraction represents <25 per cent of the total weight due to the presence of numerous clasts, including boulders exceeding 200 mm in diameter. These differences confirm the operation of

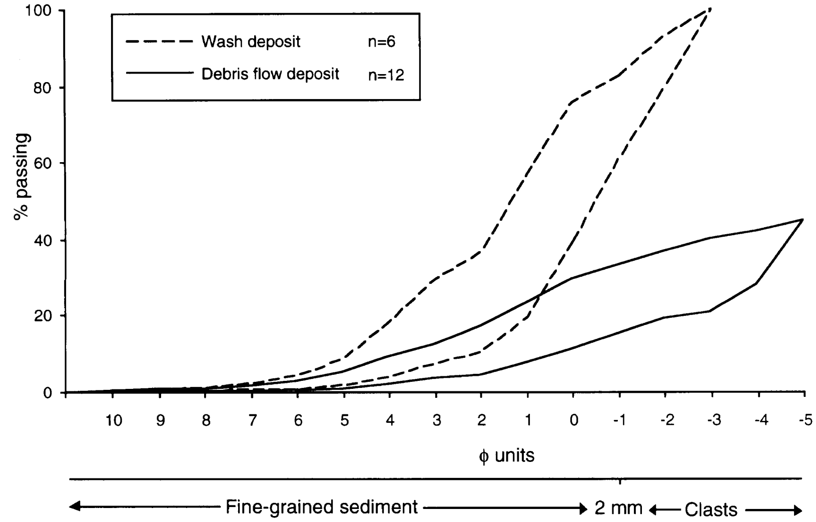

Figure 7. Cumulative particle-size envelopes for slopewash deposits and debris-flow units, for particles finer than 64 mm. Truncation of the envelope for debris-flow deposits reflects the fact that on average only 45 per cent by weight of constituent particles are finer than 64 mm (see text)

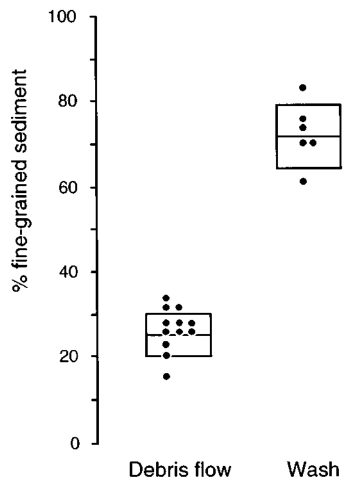

Figure 8. Percentage by weight of sediment finer than 2 mm (–1ϕ) in bulk samples from the debris-flow units and slopewash deposits

two very different depositional processes. Overall, sediment finer than 2 mm accounts for 61·1–82·8 per cent by weight of the wash units, with a mean of 72·0 per cent and a standard error of 3·2 per cent. In contrast, sediment finer than <2 mm constitutes only 15·4–33·2 per cent by weight of the debris-flow units, with a mean value of 26·4 per cent and a standard error of 1·6 per cent (Figure 8). This mean figure is slightly lower than the value of *c*. 30 per cent by weight calculated by Salt and Ballantyne (1997) for the proportion of sediments finer than 2 mm within a talus accumulation in northwest Scotland. However, given the much higher proportion of fine (<2 mm) sediment present in the wash deposits, it seems reasonable to suggest that the overall proportion of sediment finer than 2 mm that is present in the Trotternish talus accumulations is of the order of 27–30 per cent by weight.

There are several possible origins of the fine fraction in the Trotternish talus accumulations. As noted above, the form of the talus slopes is consistent with a rockfall origin, and their internal structure indicates extensive reworking by debris flows and surface wash. In terms of this interpretation, the fine sediment present may

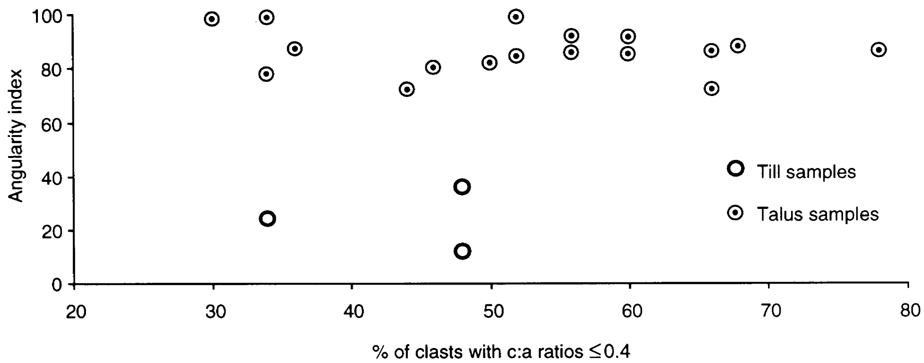

Figure 9. Plot of angularity index (percentage of clasts that are very angular, angular or subangular) against a shape index (percentage of clasts with *c*:*a* ratios ≥0·4) for 17 samples from the debris-flow units in the talus and for three samples of *in situ* till

represent: (1) granular weathering of the rock face, with fine particles falling onto and being washed into the talus; (2) inwash of fines derived from plateau-top deposits above the crest of the slope; (3) *in situ* weathering of fallen clasts (cf. Statham and Francis, 1986); or (4) addition of exotic fines blown onto the talus from another source. Alternatively, the high proportion of fines present may indicate that the deposit is primarily of glacigenic origin, but modified by the subsequent addition of rockfall debris and reworked by debris flows and wash, an interpretation consistent with both the form and internal structure of paraglacially reworked tills in recently deglaciated terrain (Ballantyne and Benn, 1994). Below, we consider first the possibility that the supposed talus accumulation may be primarily of glacigenic origin, then the origin of the fine fraction.

Rockfall versus glacigenic origin

To establish the origin of the sediments underlying the talus slopes, various attributes of these deposits were compared with those of three nearby till sections. Samples of clasts from the talus deposits were compared with those of the till sections in terms of shape and angularity, and the fine components of the talus were compared with those of the tills in terms of particle-size distribution and mineral magnetic characteristics.

The lengths of the three orthogonal axes of samples of 50 clasts were measured for 18 samples from various depths within the talus deposits and three samples of till, and all clasts were allocated an angularity category using the procedure outlined by Benn and Ballantyne (1994). For all samples, the aggregate clast shape was calculated in terms of the percentage of clasts with *c*:*a* axial ratios ≤0·4 (Benn and Ballantyne, 1993), and aggregate angularity was calculated as the percentage of clasts in each sample that fell into the combined categories of very angular, angular and subangular. The results (Figure 9) suggest that not only are the samples of till clasts generally more equidimensional, but also that they contain a much smaller proportion of very angular, angular and subangular clasts (<40 per cent, as opposed to >70 per cent for all talus samples). The differences in angularity are significant at $p < 0 \cdot 01$ (Mann–Whitney two-sample test), and consistent with the distinction between clasts that have been rounded by abrasion at the glacier sole and those that have escaped such modification (Benn and Ballantyne, 1994). Moreover, several basalt clasts from the tills exhibited striae, but no striated clasts were found in the talus samples. Finally (though less conclusively, in view of the difference in location), a small number of igneous intrusive and sedimentary erratics occur in the tills, but none were detected in the talus samples, which comprised basalts and tuffs similar to those that crop out in the cliff upslope.

The particle-size distributions of six samples of sediment finer than 8 mm from talus, and six from the till sections, were determined through a combination of wet sieving from 8 mm down to 500 µm and Coulter Counter analysis of the fine residue. The results (Figure 10) reveal marked differences between the two groups of samples. With one exception, the dominant mode for the talus samples lies in the coarse sand to fine gravel range, whilst that for the till samples falls, again with one exception, in the coarse silt to fine sand range. This distinction is reflected in differences in the graphic means calculated for the <8 mm fraction: those of the talus samples range from 1·0ϕ to 2·0ϕ, and those of the till samples from 2·67ϕ to 5·33ϕ (Figure 10). Testing using

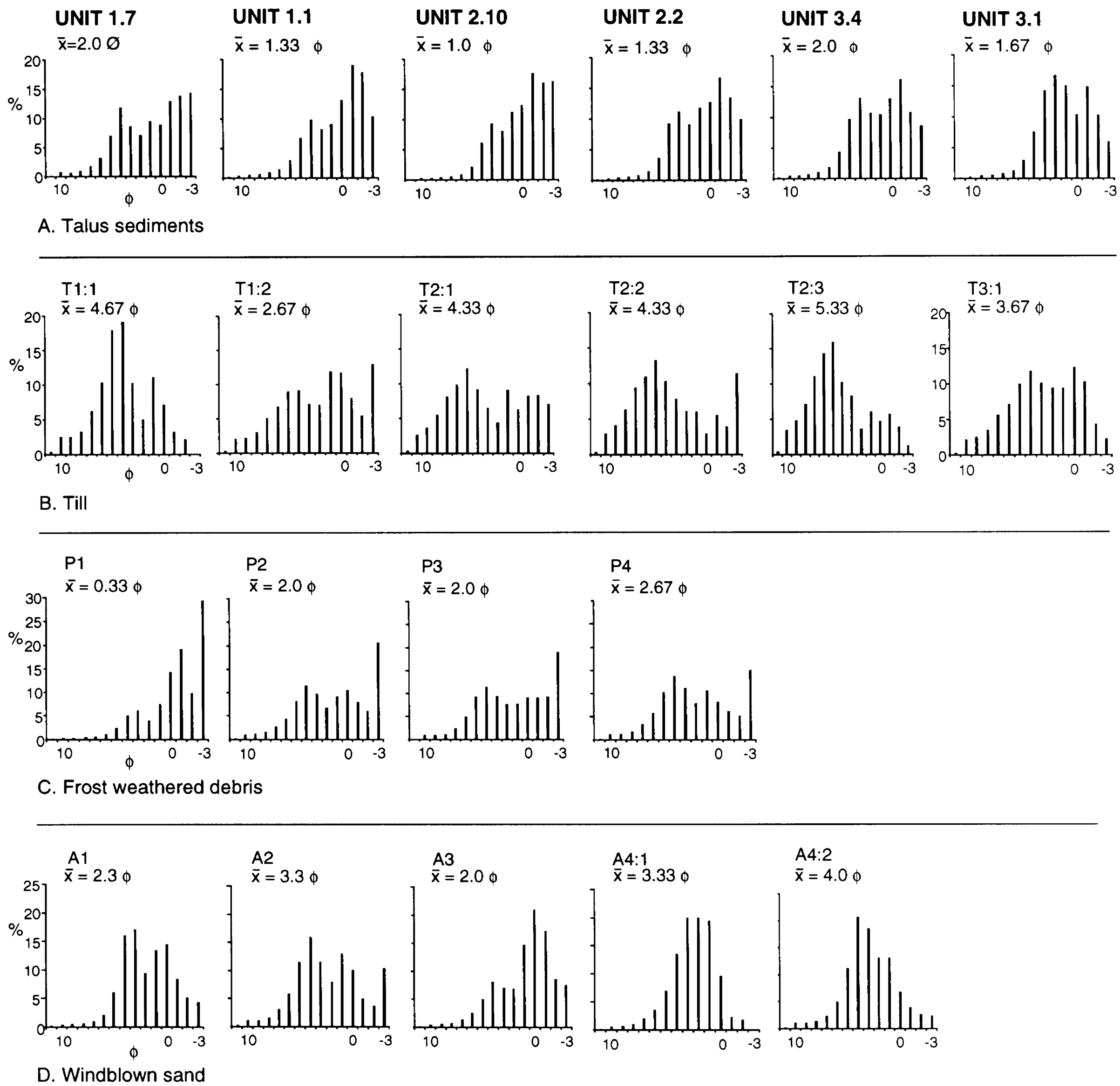

Figure 10. Particle-size distributions for material finer than 8 mm (−3ϕ). (A) Samples from debris-flow units within the talus. (B) Samples from nearby *in situ* tills. (C) Samples from *in situ* frost-weathered debris on the summit plateau of The Storr. (D) samples of aeolian sediment from the summit plateau of The Storr

Kolmogorov–Smirnov two-sample tests showed that though all the talus sample distributions are statistically indistinguishable from each other, all but one differ from all the till sample distributions at $p<0{\cdot}01$. Silt plus clay (<63 μm) constitute >30 per cent of all till samples, probably reflecting comminution of fines by subglacial abrasion, but <10 per cent of all of the talus samples, again suggesting that the talus sediments have not experienced subglacial modification.

Mineral magnetic analyses were also performed to test if the compositional properties of the talus units are different from those of the till samples. Using the method of Walden *et al.* (1996), analyses were performed on two discrete size fractions (8–1·4 mm and <1·4 mm). Figure 11 summarizes the results, in terms of Saturation Isothermal Remanent Magnetism (SIRM) plotted against the 100 mT backfield ratio. SIRM can be interpreted

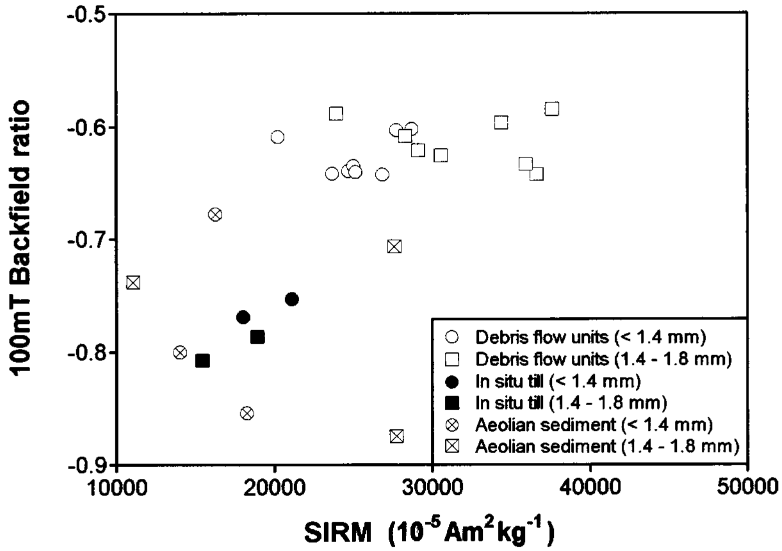

Figure 11. Plot of 100 mT backfield ratio against SIRM (10^{-5} Am^2 kg^{-1}) for both coarse (1·4–8·0 mm) and fine (<1·4 mm) size fractions of sediments derived from the debris-flow units within the talus, a nearby exposure of *in situ* till and aeolian sediments sampled on the summit plateau of The Storr. See text for explanation

as a concentration-dependent parameter, values being roughly proportional to the overall concentration of ferrimagnetic and anti-ferromagnetic iron oxide minerals. The 100 mT backfield ratio is concentration-independent and reflects the overall balance between these two magnetically distinct mineral groups. Figure 11 shows not only that the talus samples contain significantly higher concentrations of magnetic minerals than the till samples, but also that the assemblage of mineral types differs, as the higher 100 mT backfield ratios for the talus samples suggest a greater proportion of anti-ferromagnetic minerals in these sediments.

The above analyses of aggregate clast shape characteristics, particle-size distribution and mineral magnetic parameters all indicate marked sedimentological distinctions between the talus sediments and those of *in situ* till deposits, and thus exclude a glacigenic origin for the former.

Origin of the fine fraction in the talus accumulation

Rejection of a glacigenic origin for the fine fraction of the talus sediments implies that these reflect either addition from outside the talus accumulation or *in situ* weathering of surface and subsurface clasts. The latter appears unlikely to be significant, given the angularity of constituent debris (Figure 9), as granular disaggregation on a scale commensurate with the observed percentage of fines would be expected to have produced a much higher proportion of subrounded or rounded clasts. Moreover, granular disaggregation tends to affect only exposed clast surfaces on Scottish mountains, and is negligible in subsurface locations (Ballantyne and Harris, 1994, p. 171). It is also implausible that the fines were washed down from the plateau above the rockwall crest, as this slopes westwards away from the crest. The possibility that the fines represent inblown windblown sediment of exotic origin was investigated by comparing the particle-size distributions of fine (<8 mm) sediments in the talus deposits with those of five samples collected from aeolian deposits on the summit plateau of The Storr, 2 km to the north (cf. Ballantyne, 1998), using the methods outlined above. Although the aeolian sediments are highly variable in granulometry (Figure 10), the mean grain sizes for the talus samples are significantly coarser than those for the aeolian samples at $p<0{\cdot}01$ (Mann–Whitney two-sample test). Analysis of mineral magnetic parameters for three samples from the aeolian deposits also revealed significant differences from those for the talus samples (Figure 11). These results suggest that the fine fraction in the talus is not dominated by particles of aeolian origin.

Exclusion of *in situ* weathering, downwash of plateau-top deposits and inblown aeolian sediment as the primary provenance of fine sediment in the talus deposits implies that the most likely source of such sediment is

granular weathering of the rockface, with fine particles falling onto and being washed into the accumulating talus. An attempt was made to test this proposition by comparing the granulometry of the six talus samples with that of four samples of *in situ* frost-weathered basalt from the summit plateau of The Storr (Figure 10). Though the range of mean grain sizes for the former is statistically indistinguishable from that for the latter (Mann–Whitney two-sample test), the forms of the two sets of distributions differ, as all of the frost-debris samples are strongly bimodal with a dominant mode at 4–8 mm that is absent from the talus samples. A stronger argument for a rockwall source is provided by the recent finding by Ballantyne (1998) that the aeolian deposit that mantles the summit plateau of The Storr (Figure 1) reflects small-scale weathering of the adjacent cliff face and transport of dislodged particles upwards onto the plateau during storms. By measuring the volume of this deposit (41 000 m^3) and the area of adjacent cliff faces, Ballantyne calculated that the plateau-top aeolian sediments imply 420–480 mm of rockwall recession by granular weathering during the Late Holocene. If such a large volume of fine sediment has been blown upwards to accumulate on the plateau, it seems reasonable to expect that equally large or larger volumes of fines detached from the cliff by weathering will have travelled downwards to accumulate in the talus deposits downslope (Hétu, 1992), favouring the rockwall as the main source of fine as well as clast-sized sediment. This conclusion is reinforced by the work of Salt and Ballantyne (1997), who employed mineralogical analyses of grains within a relict talus accumulation at Knockan on the Scottish mainland to demonstrate that these were derived from the rockwall upslope. As an estimated 27–30 per cent of the Trotternish talus accumulation consists of sediment finer than 2 mm, this conclusion implies that a similar proportion of cliff retreat at the study site reflects release of fines by granular disintegration rather than the fall of clast-sized particles.

IMPLICATIONS FOR TALUS SLOPE EVOLUTION

Models of talus slope development are divided between those that consider such slopes as the product of discrete rockfall events alone (Statham, 1973, 1976; Kirkby and Statham, 1975), and those that envisage secondary transfer of debris down the upper straight slope (Francou and Manté, 1990; Francou, 1991). A variety of mechanisms have been invoked to explain such secondary movement, including rockfall impact, ‘dry avalanching’, translational failure, solifluction, snow avalanches, debris flow and surface runoff (e.g. Howarth and Bones, 1972; Carniel and Scheidegger, 1976; Carson, 1977; Church *et al*., 1979; Gardner, 1979; Whitehouse and McSaveney, 1983; Caine, 1986; Luckman, 1988), with finer grades of debris being displaced also by needle-ice creep and small-scale debris slides (Pérez, 1988, 1993). Statham and Francis (1986) have attempted to reconcile the contrasting explanations of talus evolution outlined above, by suggesting that though talus form is primarily controlled by the impact energy of falling clasts, internal weathering of talus debris may lead to the production of fines that reduce the permeability of the debris mass, promoting shallow debris slides that periodically redistribute material downslope.

Although the form of the Trotternish talus slopes appears consistent with a rockfall origin, the observations reported above suggest a rather different sequence of events. The high (*c*. 27–30 per cent) proportion of fine sediment present within the talus indicates syndepositional accumulation of both fine and coarse debris from the rockwall. The structure of the deposits demonstrates episodic reworking of the upper rectilinear slope by debris flows. As openwork deposits without a significant infill of fines are free-draining and thus unlikely to promote debris flow, it appears that the infill of fines within the Trotternish talus accumulation has been of critical importance in influencing slope evolution by facilitating periodic failure and flow of debris down the upper straight slope. Debris flows have been reported on talus slopes in a wide range of environments (e.g. Jahn, 1976; Rapp and Nyberg, 1981; Larsson, 1982; Kotarba and Strömquist, 1984; Van Steijn *et al*., 1988; Jonasson *et al*., 1991; Kotarba, 1992; Luckman, 1992; Van Steijn, 1995), suggesting that the pattern of events evident from the structure and sedimentological composition of the Trotternish talus is common. In more general terms, the findings reported above suggest that models that treat talus slopes simply as accumulations of free-draining coarse debris (e.g. Statham, 1973, 1976; Kirkby and Statham, 1975; Carson, 1977) have limited value in explaining the development and behaviour of such slopes. Conversely, the present study lends support to those models that envisage mass-transport of debris as well as rockfall deposition on the upper straight slope

(Francou and Manté, 1990; Francou, 1991), and emphasizes the role of episodic debris flows as the primary agent of sediment redistribution.

CONCLUSIONS

1. Sections up to 3·5 m deep cut through relict, vegetated talus slopes at the foot of the Trotternish escarpment in northern Skye are composed of stacked matrix- and clast-supported diamictons, intercalated with occasional slopewash horizons and buried organic soils. The fabrics and structures of the diamictons indicate emplacement by episodic debris flows of sediment reworked from further upslope. Radiocarbon dating of the deepest buried soils indicates that sediment reworking by debris flow commenced prior to 5·9–5·6 Cal ka BP, and has continued intermittently throughout the late Holocene.
2. Particle-size analyses of the talus sediments indicates that debris-flow units contain an average of 26·4 per cent sediment finer than 2 mm, and that slopewash horizons contain on average 72·0 per cent sediment finer than 2 mm, suggesting that the overall proportion of fines <2 mm within the talus is approximately 27–30 per cent.
3. Comparison of the characteristics of the talus sediments with those of nearby till exposures excludes a glacigenic origin for the former. The angularity of constituent clasts indicates that *in situ* weathering of talus debris is unlikely to have contributed significantly to accumulation of fines in the deposit, and sedimentological comparison with nearby windblown sands suggests that an aeolian origin is unlikely. We conclude that the fine sediment within the talus is derived primarily by granular weathering of the rockwall upslope, with syndepositional accumulation of both fine and coarse debris. This interpretation implies that *c*. 27–30 per cent of rockwall retreat since deglaciation reflects granular weathering rather than rockfall.
4. The presence of abundant fines within the talus deposits is inferred to have been of critical importance in facilitating build-up of porewater pressures, leading to episodic failure and flow of debris on the upper parts of the slope.
5. Though there is limited information on the internal structure of talus, the frequency of debris flows on talus slopes in a wide range of environments suggests that most contain concentrations of fines at shallow depths. This implies that the mechanical properties of talus cannot be regarded as those of a free-draining granular sediment, and that models that treat talus slopes as simple accumulations of coarse clasts have limited value in explaining their nature and evolution. The present findings lend support to models that envisage the upper straight slope on talus accumulations as the product of mass transport as well as rockfall deposition, and indicate that episodic debris flow has been the primary agent of mass-transport at this site.

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